Gamma Spectrometry of Shielded Sources

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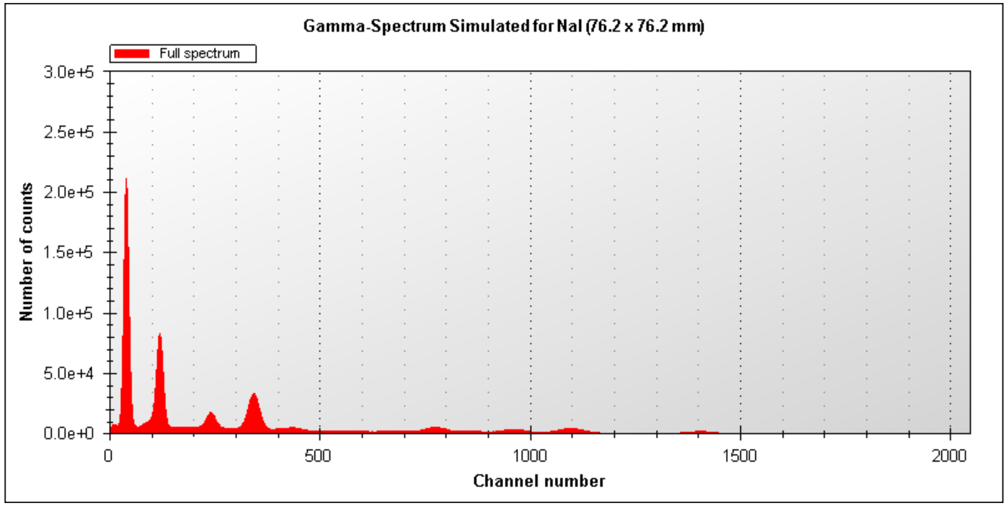
Outline

- Theoretical considerations
- Gamma Spectrum Simulator
- Live demonstration

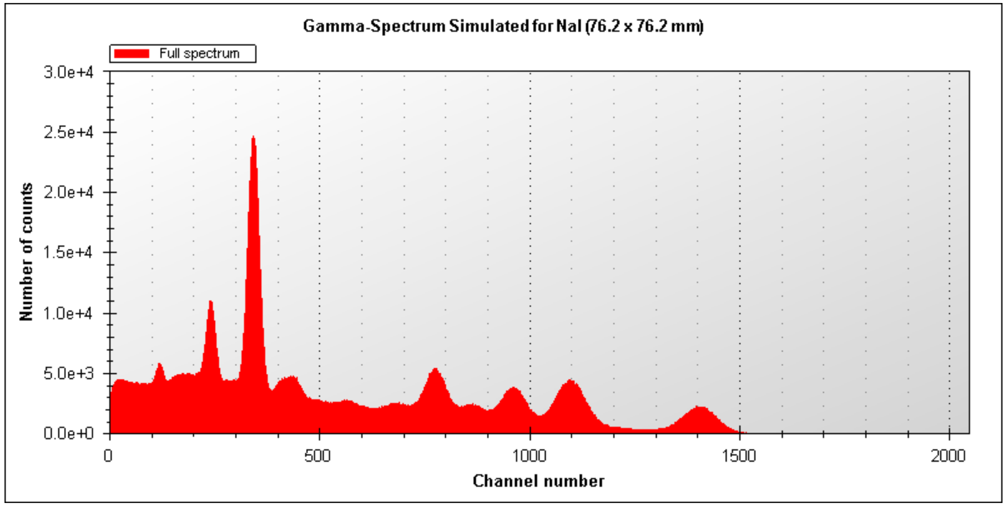
nucleonica

Unshielded

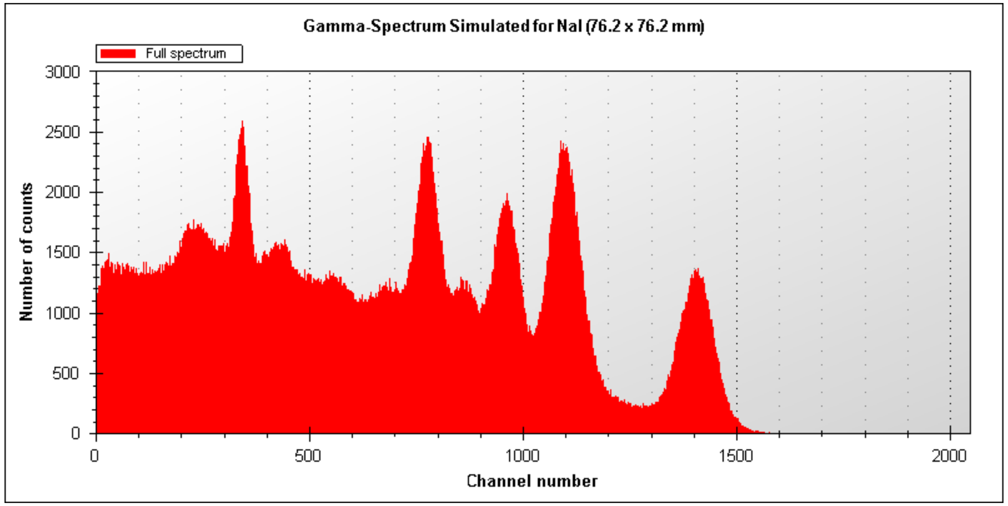


NaI (3‘‘x3‘‘), Eu-152, 1 MBq, 1000 s, 25 cm from detector, point source

Shielded with 1 mm lead

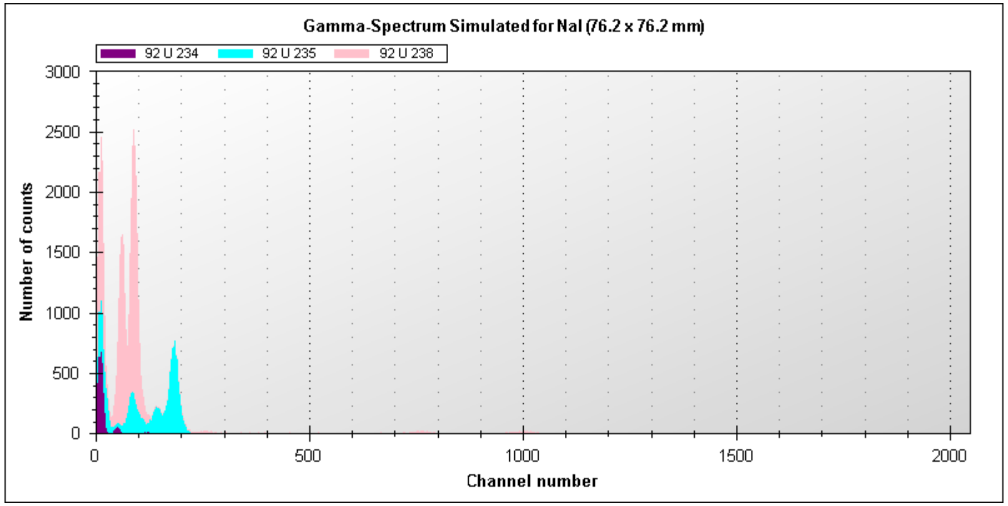


Shielded with 10 mm lead



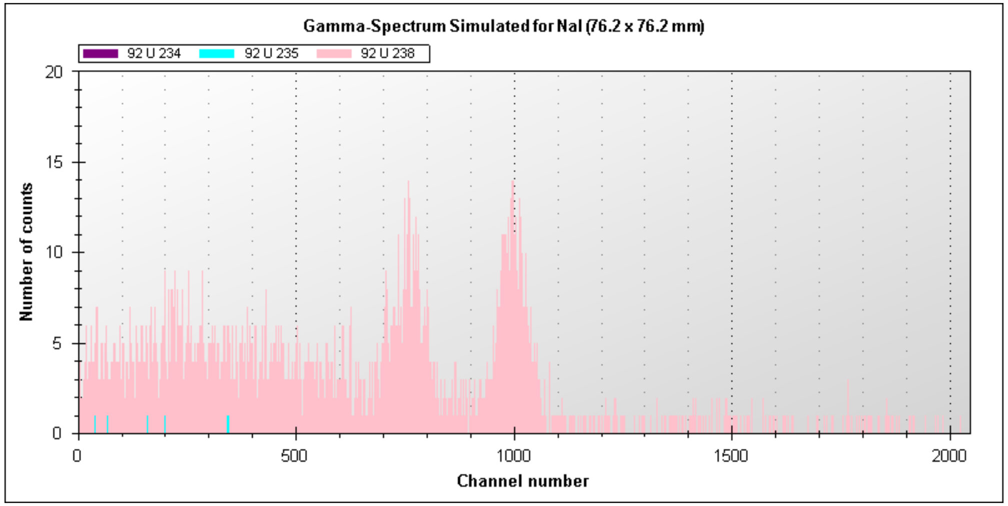
Theoretical considerations

Unshielded

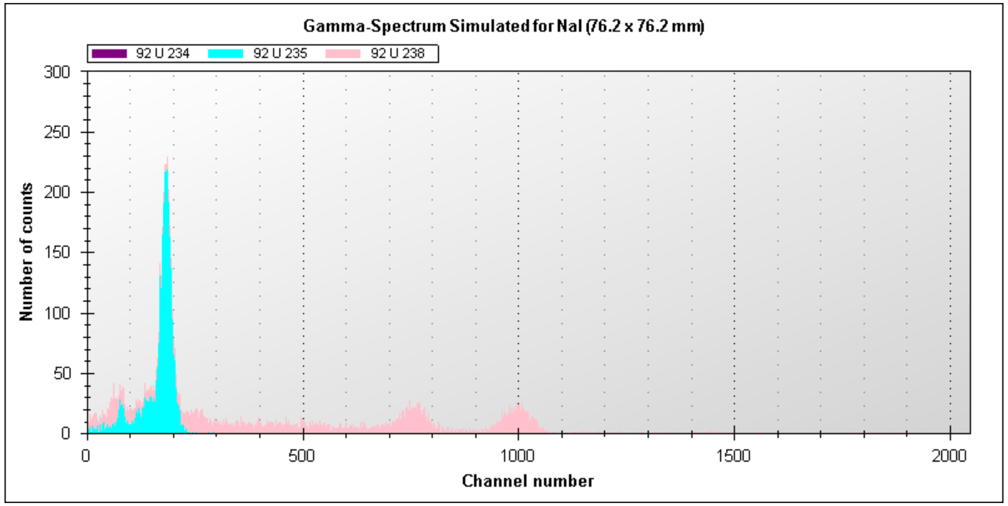


NaI (3‘‘x3‘‘), NatU 1g, 10000 s, 25 cm from detector, point source

Shielded with 10 mm lead



Shielded with 1 mm lead



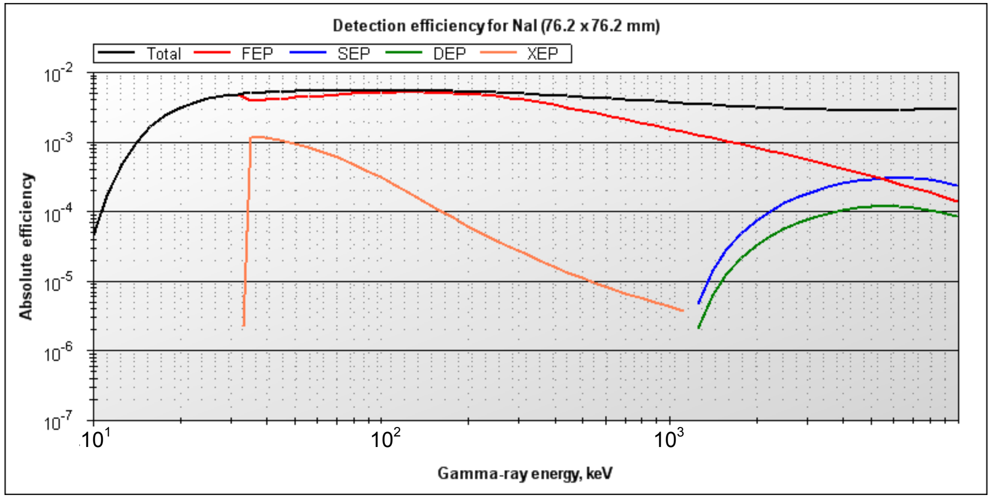
Basic effects of shielding:

- Spectrum shape changes drastically (low-energy lines disapear, high-energy lines start to give major contribution to the spectrum),
- Count rate can significantly decrease => influence of background => detectability considerations,
- Signatures of some nuclides can completely disapear (loss of information) => this is the worst case because it is not possible to predict characteristics of the source based on such measurements.

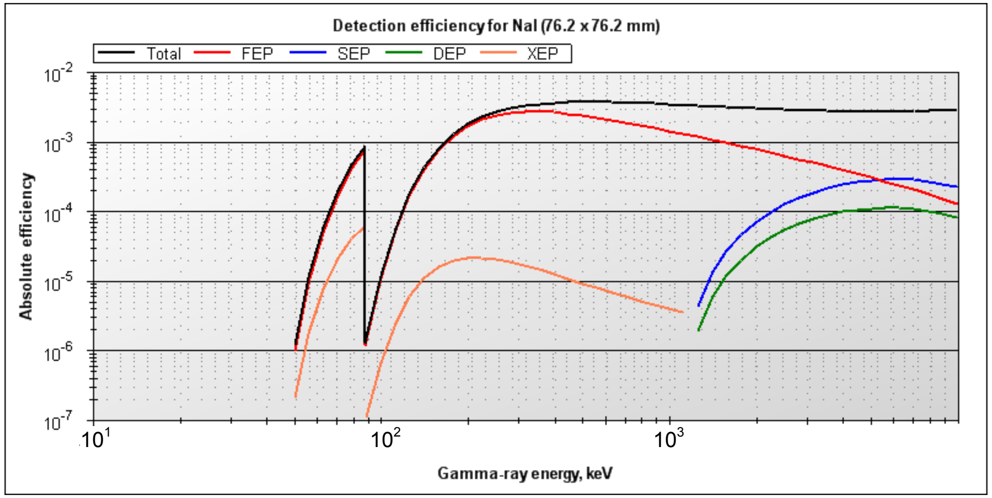
Theoretical considerations

Detection efficiency of NaI (3‘‘x3‘‘)

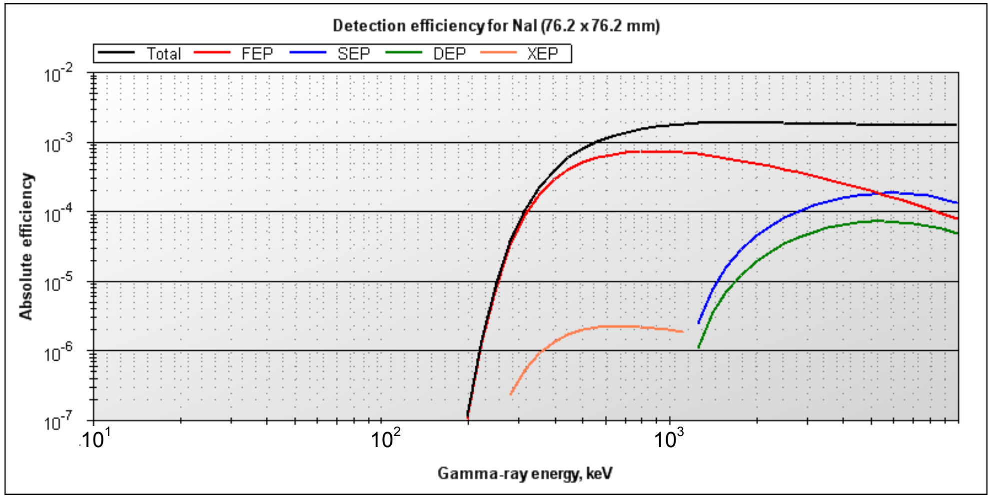
Unshielded



Shielded with 1 mm lead



Shielded with 10 mm lead



Correction for the attenuation in shielding

The full energy peak (FEP) count rate in the case of

unshielded source:

$$I_U = S_U / t_U = A \gamma \varepsilon_U$$

shielded source:

$$I_S = S_S / t_S = A \gamma \varepsilon_S$$

S – the area of the full energy peak,
t – the measurement time interval,
A – the activity of a source.

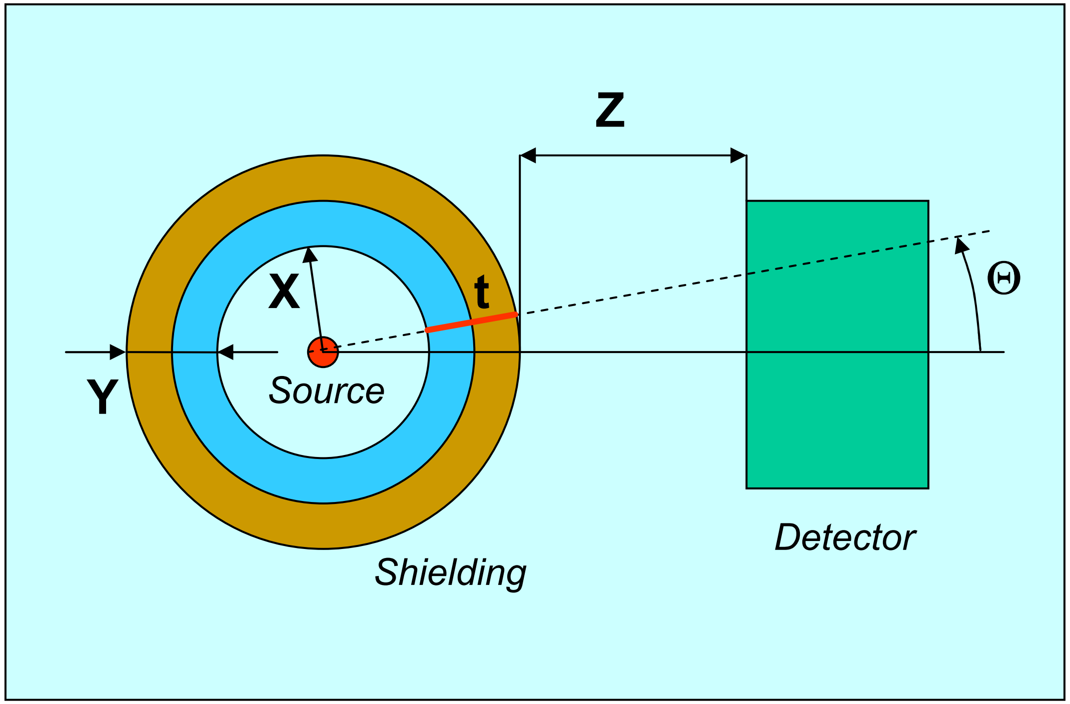
ε – the FEP detection efficiency,
γ – the gamma-ray emission probability,

The unshielded peak count rate can be derived from the measurement of a shielded source as:

$$I_U = K I_S$$

where $K = \varepsilon_U / \varepsilon_S$ is the energy dependent attenuation correction factor.

Isotropic point source and spherical shielding



$$K = exp(\mu_{abs} Y)$$

t = Y - the photon pathway in the shielding (cm) - does not depend on the angle Θ !

μ_{abs} - photon attenuation coefficient (1/cm) describing the absorption of photons in the shielding

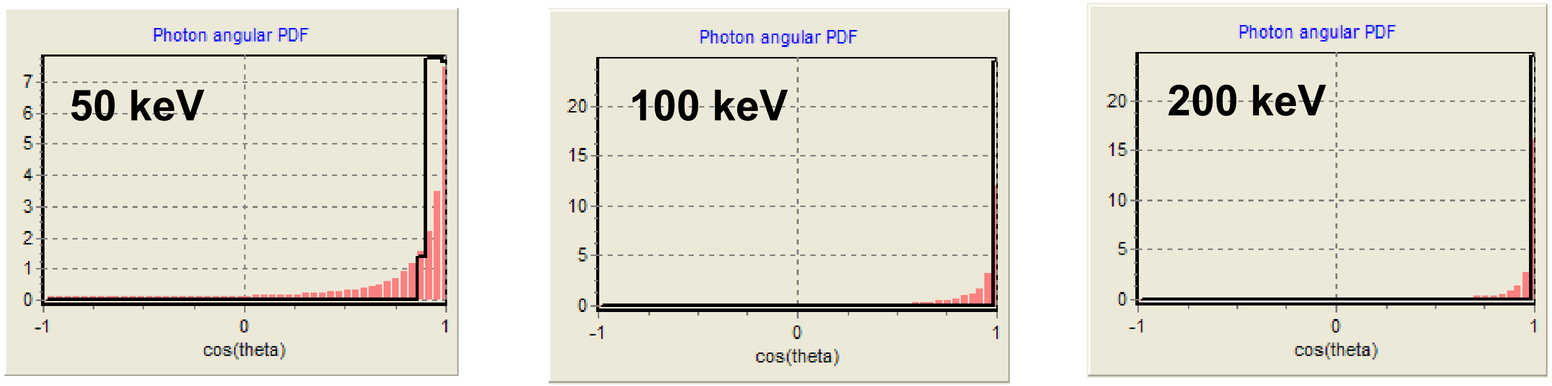
For multiple layer shielding: $\mu_{abs} Y = \Sigma_i (\mu_{abs} Y)_i$ - the sum over all shielding layers

Is μ_{abs} equal to μ_{tot}?

$$\mu_{tot} = \mu_{photoeffect} + \mu_{compton\ scattering} + \mu_{pair\ production} + \mu_{coherent\ scattering}$$

Coherent scattering = Rayleigh scattering – the incident photon is absorbed by the atomic shell and re-emitted in the other direction without changing its energy.

Coherent scattering angular distribution Probability Density Functions (PDF) for Pb:

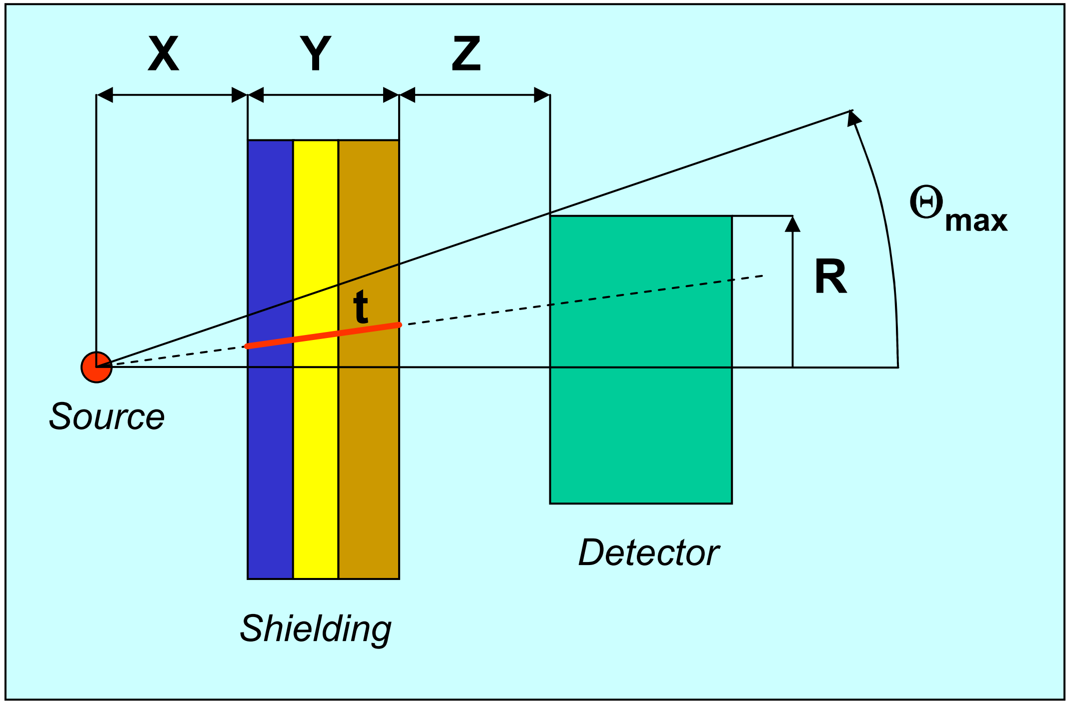


Normally better results are obtained by assuming that:

Approximation !!! $\mu_{abs} = \mu_{tot}$ **for** $E_\gamma < 100$ **keV**

$\mu_{abs} = \mu_{tot} - \mu_{coherent\ scattering}$ **for** $E_\gamma > 100$ **keV** **Approximation !!!**

Isotropic point source and slab shielding



$$K = \frac{\int_{\cos\Theta_{max}}^{1} \varepsilon_0(\Theta)\, d\cos\Theta}{\int_{\cos\Theta_{max}}^{1} \varepsilon_0(\Theta)\, exp(-\mu_{abs} t(\Theta))\, d\cos\Theta}$$

$$\cos\Theta_{max} = \frac{X+Y+Z}{\sqrt{R^2+(X+Y+Z)^2}}$$

$t(\Theta) = \dfrac{Y}{\cos\Theta}$ - the thickness of shielding at angle Θ

$\varepsilon_0(\Theta)$ - the FEP efficiency for a pencil photon beam striking the detector at angle Θ

Small detectors or/and large source-to-detector distances: $X+Y+Z >> R \quad (i.e.\ \cos\Theta_{max} \approx 1)$

Underestimation !!! $K \approx exp(\mu_{abs} Y)$ **Underestimation !!!**

Theoretical considerations

Case study: ∅5x5 cm NaI and Pb slab shielding

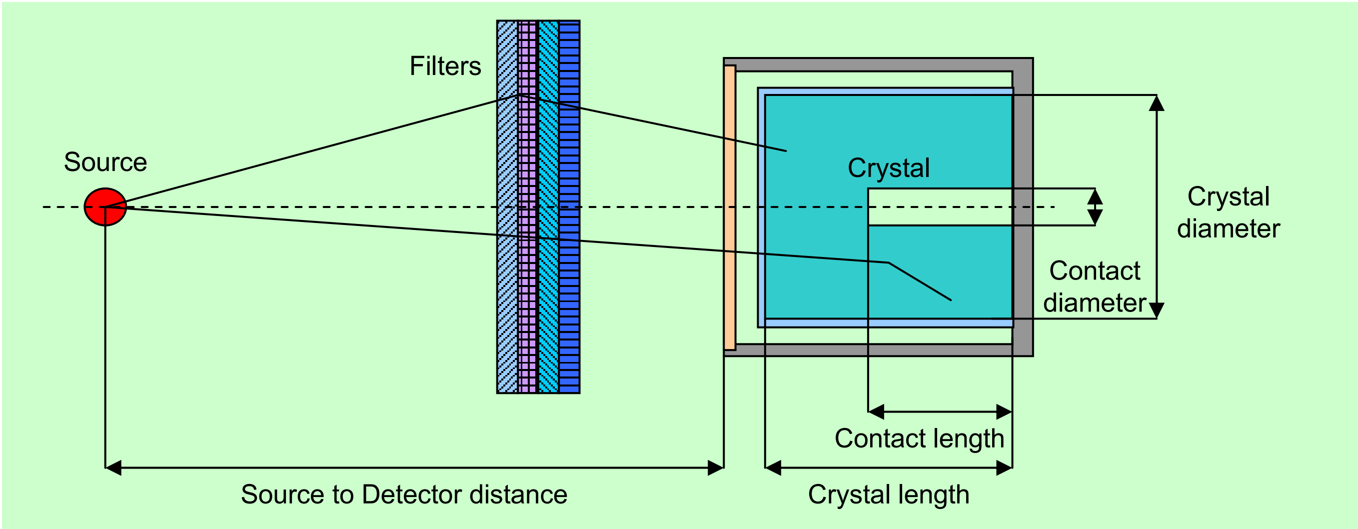
E_γ, keV	Y, cm	Integration with $\mu_{abs} = \mu_{tot} - \mu_{coh}$		K = exp(μ_{abs}Y)	
		X+Y+Z = 5 cm	X+Y+Z = 50 cm	$\mu_{abs} = \mu_{tot} - \mu_{coh}$	$\mu_{abs} = \mu_{tot}$
100	0.1	588.5	438.3	423.7	538.0
	1.0	$1.54 \cdot 10^{27}$	$2.61 \cdot 10^{26}$	$1.86 \cdot 10^{26}$	$2.03 \cdot 10^{27}$
	5.0	$3.01 \cdot 10^{133}$	$1.22 \cdot 10^{132}$	$2.20 \cdot 10^{131}$	$3.50 \cdot 10^{136}$
500	0.1	1.19	1.19	1.19	1.20
	1.0	5.81	5.46	5.44	6.16
	5.0	6510	4850	4780	8880
1000	0.1	1.08	1.08	1.08	1.08
	1.0	2.22	2.16	2.16	2.23
	5.0	54.3	47.5	47.6	55.0

Conclusions (slab shielding)

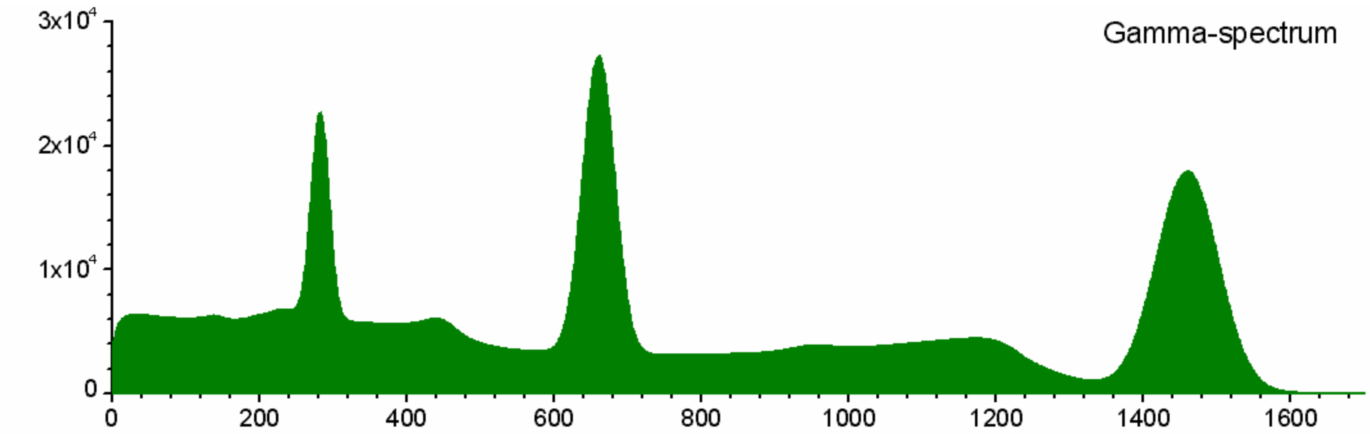
- **The use of exact formula(s) for K is highly recommended when accurate evaluation of the activity of a shielded source is required.**
- **In the far measurement geometries the approximation K=exp(μ_{abs}Y) with $\mu_{abs} = \mu_{tot} - \mu_{coh}$ is quite accurate. In the close geometries it gives underestimated values of the shielding correction factor.**
- **Even though it is not entirely correct, the approximation K=exp(μ_{abs}Y) with $\mu_{abs} = \mu_{tot}$ is more preferable in close measurement geometries as it conservatively overestimates the attenuation properties of a shield.**
- **General recommendation: One should avoid, if possible, measurements of shielded sources in close geometries.**

NUCLEONICA: Gamma-Spectrum Simulator

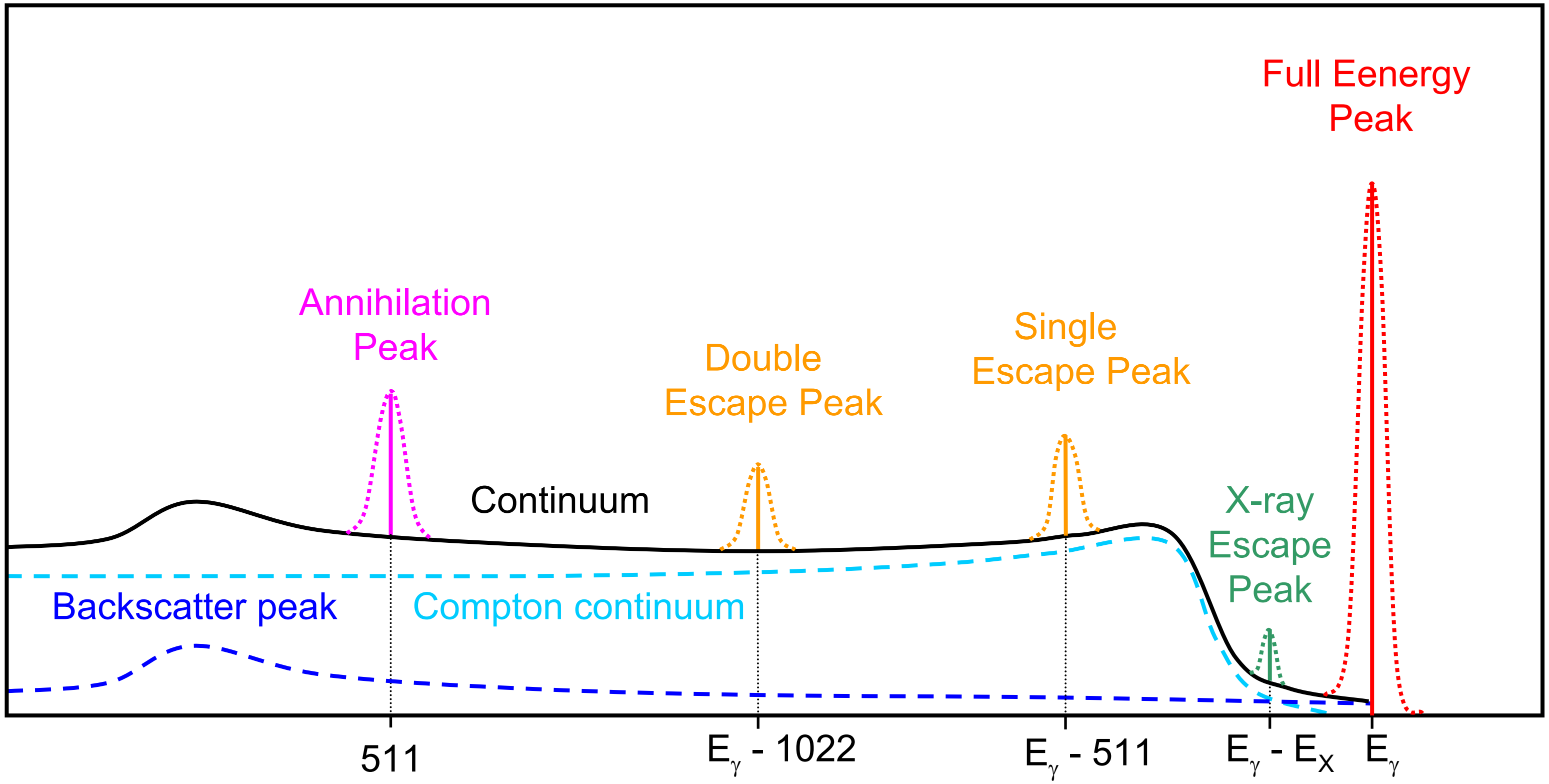
Measurement setup model implemented:



Spectrum modeling procedure:



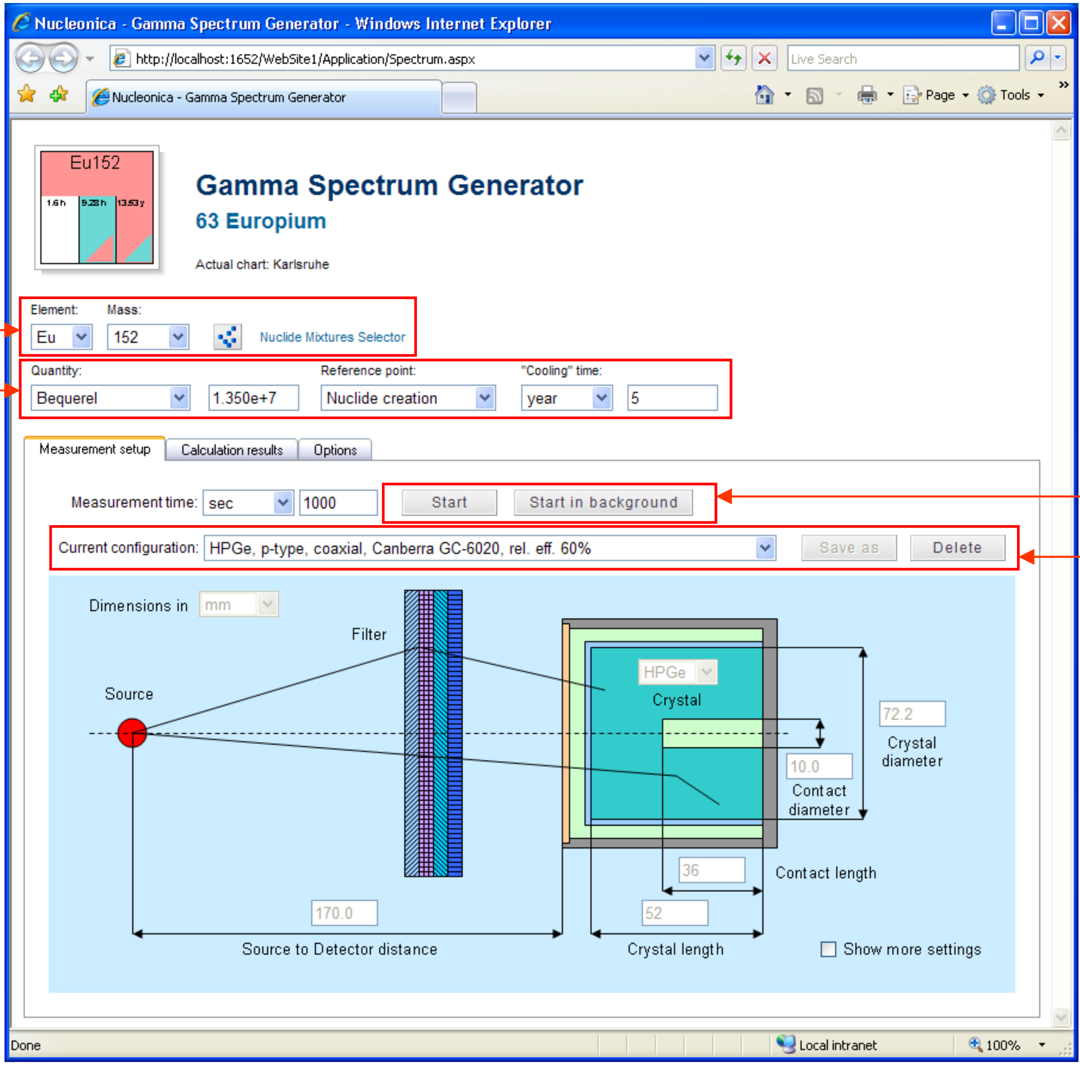
Detector response profile model:



Features implemented: Measurement setup

An arbitrary individual nuclide or a pre-defined mixture of nuclides can be selected as a radiation source

The quantity (activity, mass or number of atoms) of a nuclide or a mixture can be specified either at the moment of its production or at the spectrum measurement starting point of time. In the former case controls for specifying duration of a source cooling time interval become available.



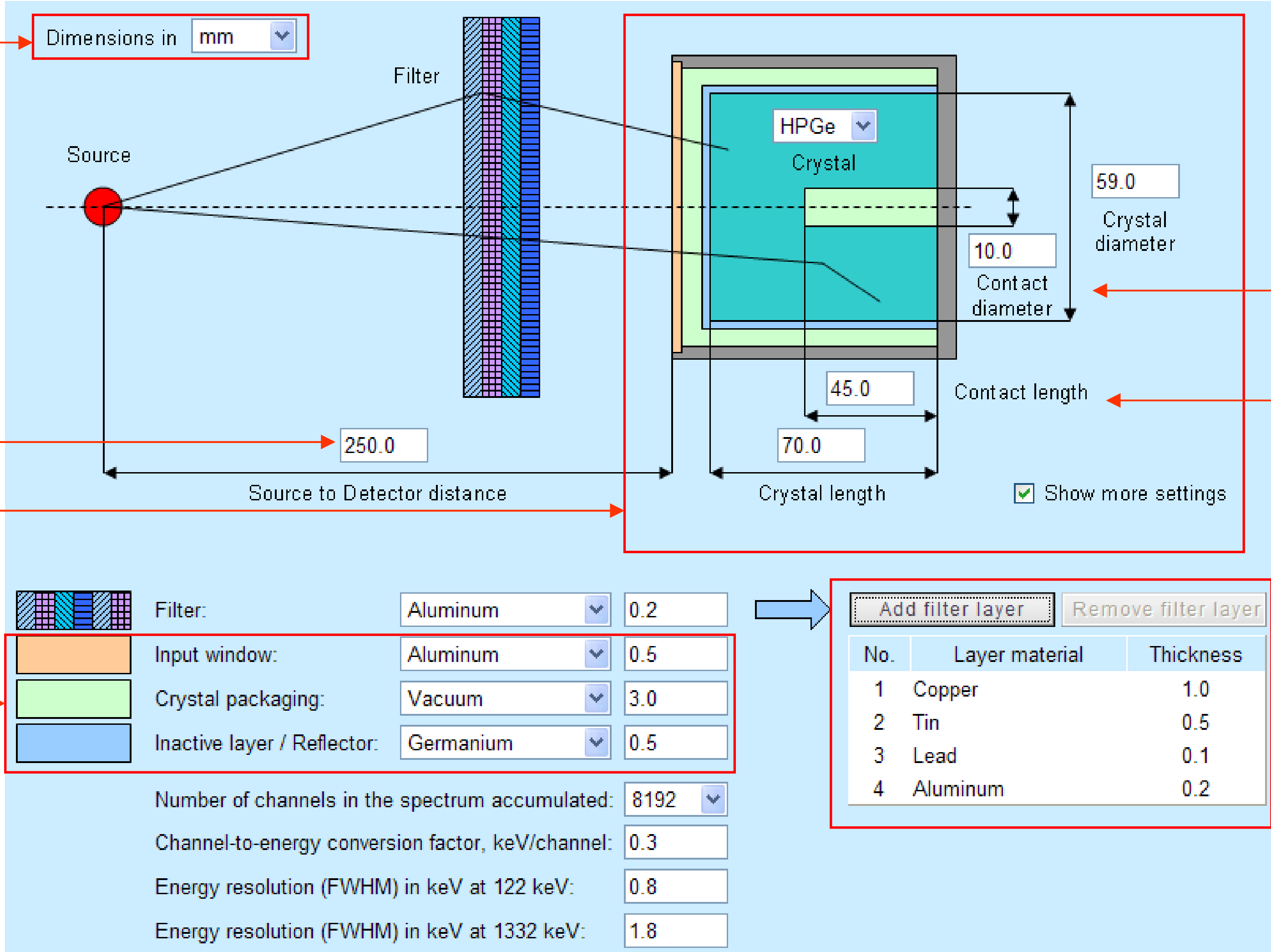
Calculations can be started on-line or in a background mode

A suitable γ-spectrometer can be chosen from 6 pre-defined configurations, which include 2 coaxial HPGe (50% and 150%) detectors, low-energy (LEGe) and broad-energy (BEGe) HPGe detectors, and 2 NaI detectors (∅3″×3″ and ∅2″×1″). In addition, user's specific configurations can be managed.

Features implemented: Measurement setup

Dimensions can be entered in “mm”, “cm” or “inch” units

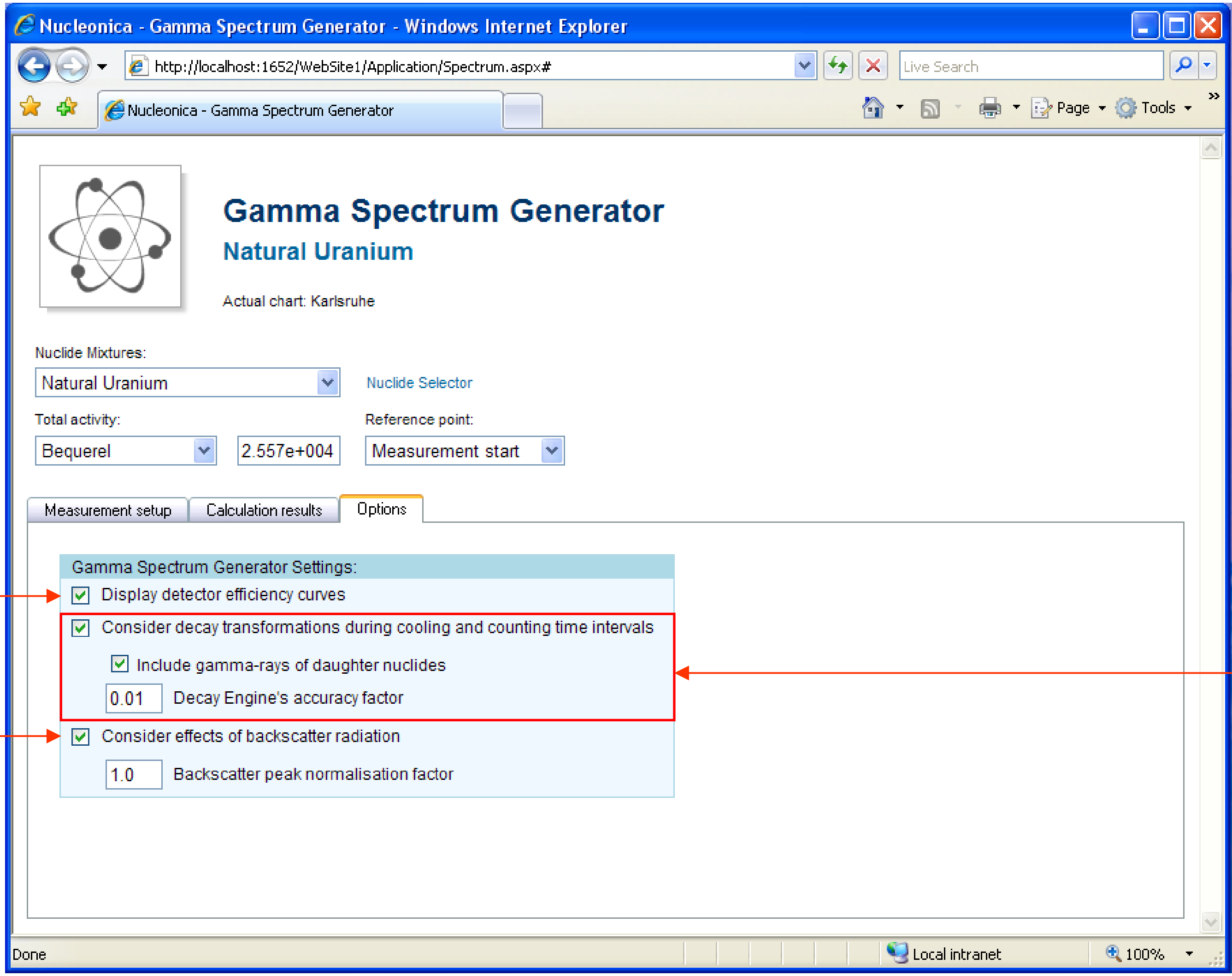
The configurable parameters include the source-to-detector distance, as well as dimensions and materials of the detector construction elements.



The dimensions of a cylindrical contact at the rear side of the crystal (a construction feature of conventional coaxial HPGe detectors) can be specified

Up to 6 additional absorbing filters made of Al, Cu, Fe, Pb, Sn, or polyethylene can be placed between source and detector

Features implemented: Options



Efficiency Graph can be activated in the Calculation Results output

The backscatter peak simulation can be switched on/off, and its contribution to the spectrum can be adjusted

Decay calculations can be enabled that will allow contributions from decay products, being accumulated during source cooling and spectrum measurement time intervals

Features implemented: Calculation results

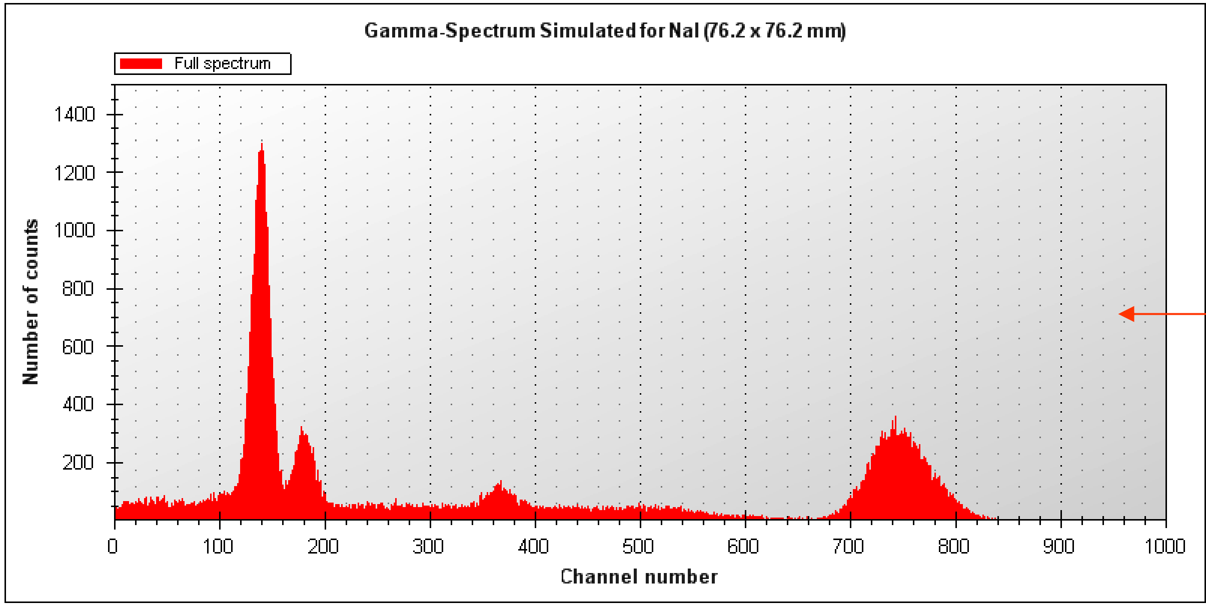
Measurement setup | Calculation results | Options

Statistical number of counts
Count rate at start
Count rate at end
Theoretical number of counts
Statistical number of counts

Data displayed: Statistical number of counts

View/Save results in Text or Excel format

Complete set of spectral information can be downloaded as a text or Excel spreadsheet file



Right click within the graph area enables a context menu, from which one can print or download the spectrum graph

Update spectrum graph

Display: ☐ Energy scale ☐ Spectrum continuum ☐ Contribution of scattered photons ☐ More graph options

Switch between channel number and energy scale; show peak, continuum and backscatter peak contributions to the full spectrum

Additional options allow to customize appearance of the graph to meet one’s needs and requirements

No.	Nuclide	Count rate at start, cps	Count rate at end, cps	Spectrum counts	Display
1	42 Mo 99	6.23E+01	6.22E+01	6.26E+04	☐
2	43 Tc 99	6.70E-15	6.79E-15	0.00E+00	☐
3	43 Tc 99m	2.69E+01	2.68E+01	2.70E+04	☐
	Total	**8.92E+01**	**8.90E+01**	**8.97E+04**	

Display nuclide specific contributions to the full spectrum

NUCLEONICA: Gamma-Spectrum Simulator

Features implemented: Calculation results

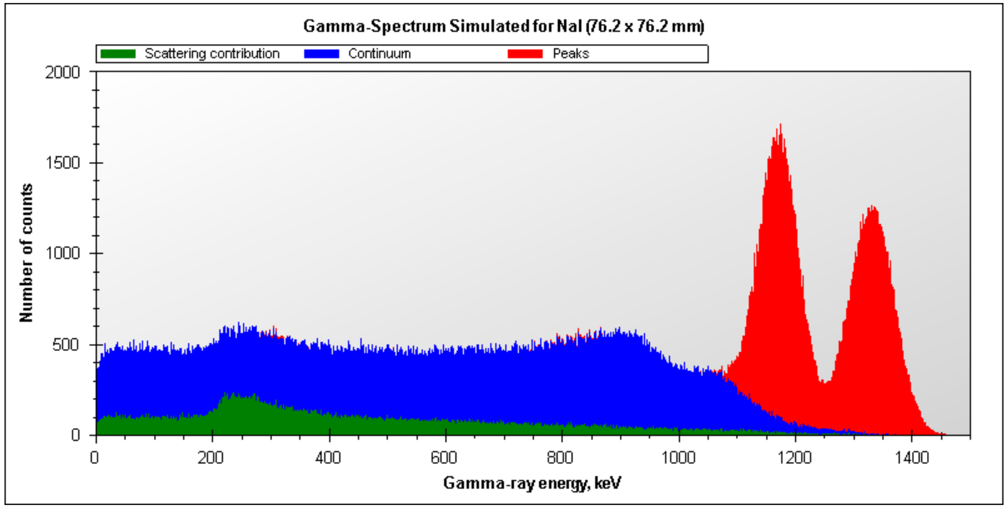
Right click within the graph area enables a context menu, from which one can print or download the efficiency graph

Select efficiency data to be displayed on the graph

Additional options allow to tailor the efficiency graph to one's needs and requirements

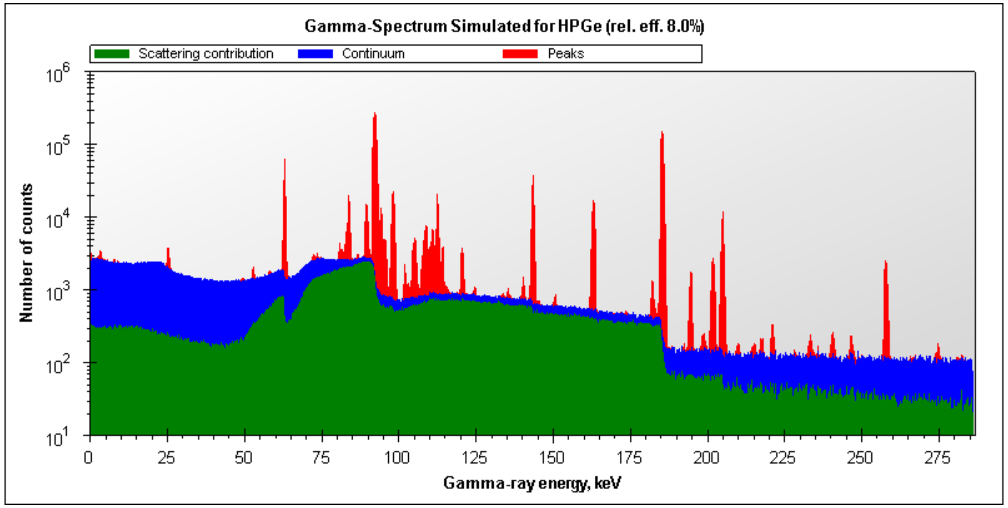
Examples:

100 kBq ^{60}Co



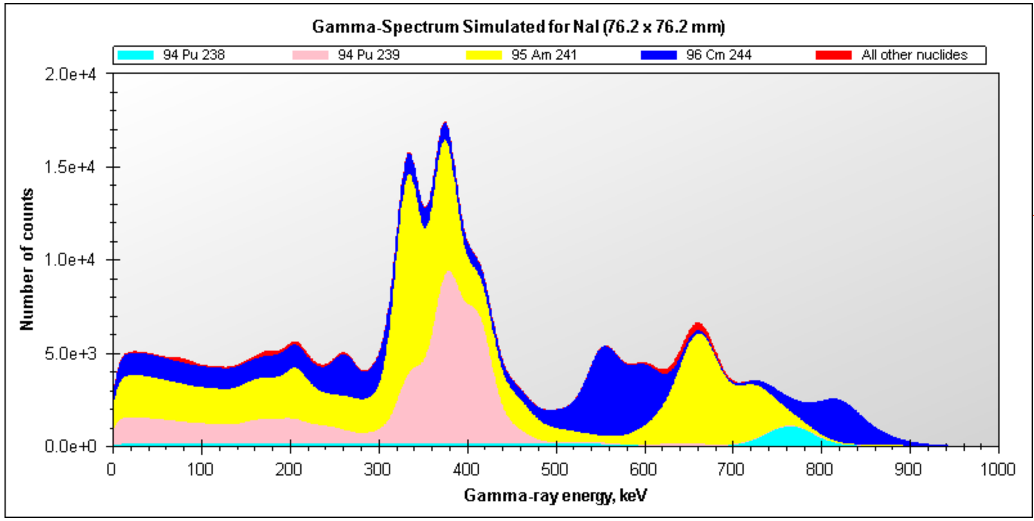
Detector - NaI (∅3″×3″)
Source-to-detector distance - 25 cm
Measurement time - 1000 s

1 g Nat U (2 years after separation)



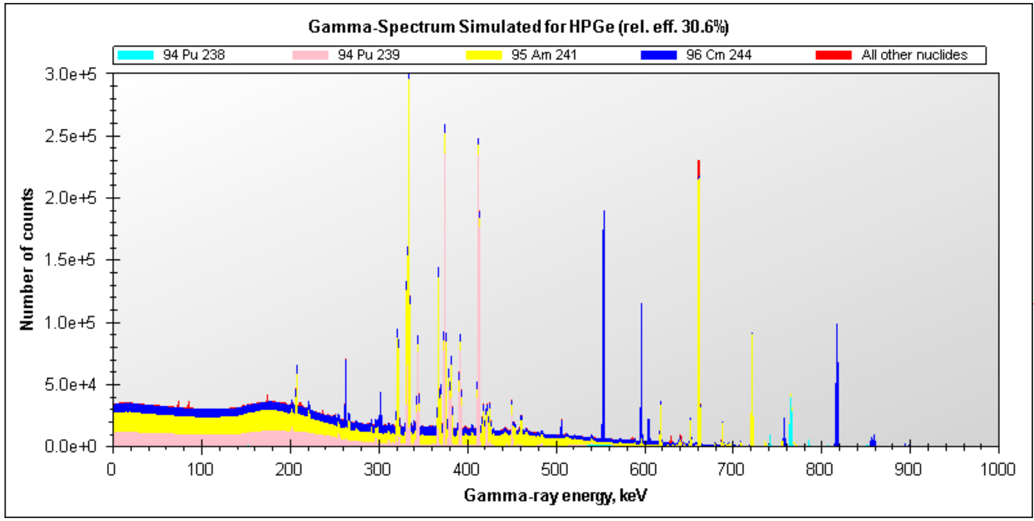
Detector – LEGe (20 mm × 2800 mm^2)
Source-to-detector distance – 25 mm
Filter – 0.5 mm Sn
Measurement time - 10^5 s

Examples:



Detector – NaI (∅3″×3″)
Source-to-detector distance – 25 cm
Filter – 5 mm Pb
Measurement time - 1000 s

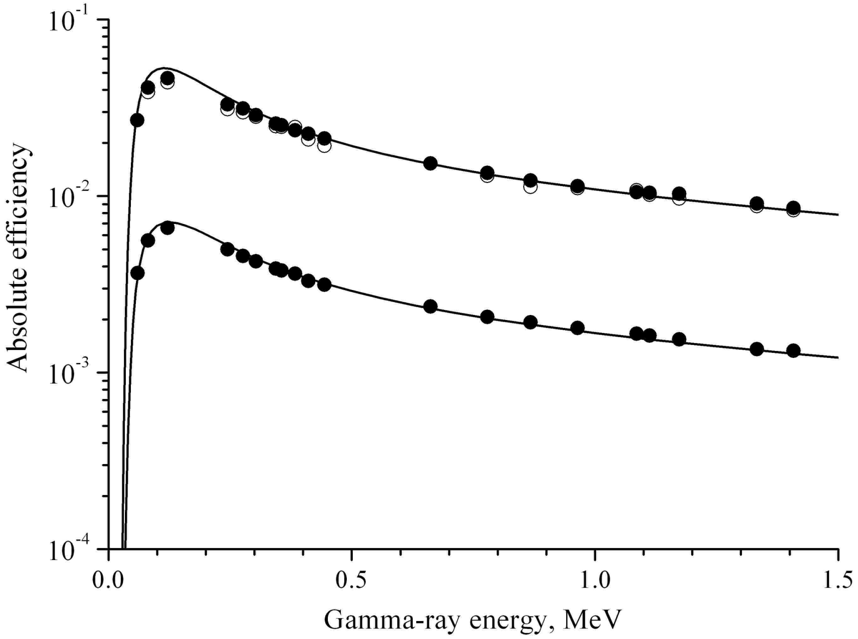
Actinides extracted from 1 kg 6-year-aged PWR spent fuel. Activity - 5.25 TBq



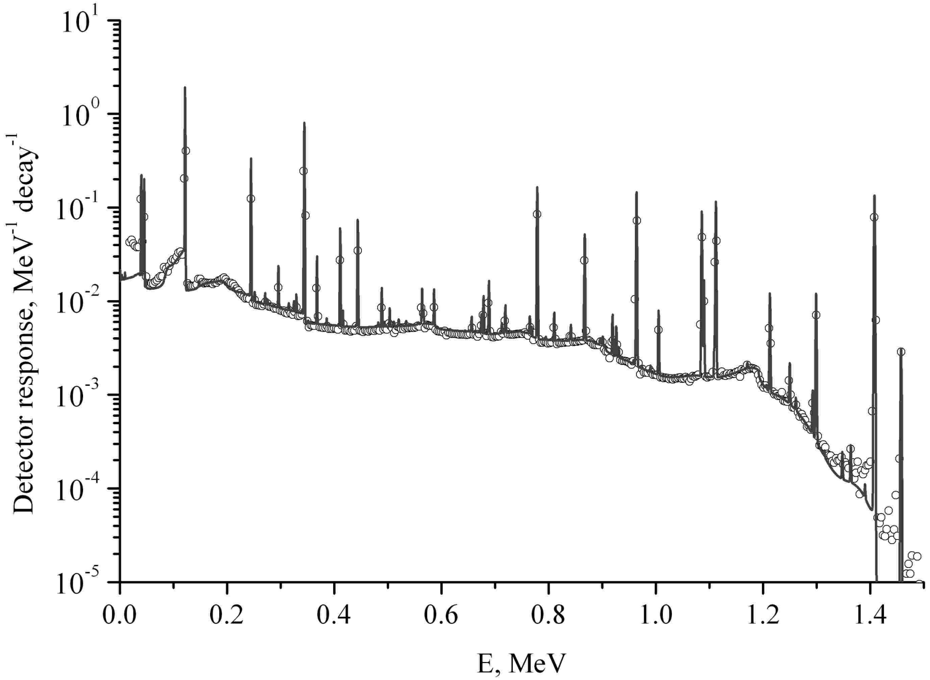
Detector – BEGe (30% rel. eff.)
Source-to-detector distance – 25 cm
Filter – 5 mm Pb
Measurement time - 1000 s

Example:

Results of the experimental validation with 60% HPGe coaxial detector



Full Energy Peak efficiency as a function of the photon energy: circles – experimental values, curve – calculated. Two sets of data refer to the source location at 5 cm and 17 cm distances from the detector end cap.



Calculated (curve) and experimental (circles) detector responses for ^{152}Eu source at 17 cm distance from the detector end cap.

Future work:

- **Include simulation of the spectrum distortion effects (e.g. due to coincidence summing and energy resolution deterioration), which may appear in measurements involving elevated count rates and small source-to-detector distances.**
- **Extend the detector response profile database to include $LaBr_3$ scintillators that, because of their much superior energy resolution, start to replace traditional NaI crystals in many applications.**
- **Include self-attenuation effects, which would allow more realistic simulation of gamma-spectra from voluminous sources.**

Live demonstration

Gamma Spectrum Generator

Thanks for your attention !

nucleonica